Modes and Progression of Tool Deterioration and Their Effects on Cutting Force during End Milling of 718Plus Ni-Based Superalloy using Cemented WC-Co Tools

Nurul Hidayah Razak

A thesis submitted to Auckland University of Technology in fulfilment of the requirements for the degree of Doctor of Philosophy

2017

School of Engineering, Computer and Mathematical Sciences

ABSTRACT

Understanding the detailed progression of cutting tool deterioration and how deterioration affects cutting force (F) during milling of difficult-to-cut Ni-based superalloys is important for the improvement of machinability of the alloys. It also serves to clarify whether and how an F-based method for monitoring tool deterioration is possible. This understanding is however far from sufficient, as is explained in this thesis after a comprehensive review of the literature. The aim of the present research is thus to determine and explain the modes and progression of tool deterioration and how cutting forces may vary due to the various deterioration features of the cutting tool edge.

Experimentally, the study started by using a typical milling condition with both uncoated and coated cemented carbide (WC-Co) tools. Milling was conducted in either dry or wet conditions. After each pass of a selected distance, the tool was examined in detail in the same manner. Thus, tool deterioration could be monitored more closely and failure mechanisms could be identified and explained. Following on the study on determining the modes of tool deterioration, the progress of deterioration and cutting forces during milling were carefully monitored. Through analysing the monitored tool deterioration features and measured force data, how edge wear, chipping and breakage in cutting edge and beyond the edge contribute to the variation of cutting forces could be studied and better understood. Furthermore, experiments have also been conducted using workpiece in a hardened state.

It has been observed that the commonly recognised build-up layer in the initial stage does not significantly affect the tool deterioration process. Instead, from the beginning of milling, cutting forces/stresses could cause small chipping locally in the initially sharp cutting edge. Fracturing locally with cracks propagating outside the cutting edge along the flank face in the subsurface region could also take place and was consistent with the direction of the cutting force. There was an initial period of time during which a number of microcracks had initiated in and near the cutting edge on the rake face side. These cracks soon propagated resulting in extensively fracturing and blunting of the tool. Coating of the tools had provided little protection as in the cutting edge area the coating had broken away soon after milling started. The major tool failure mode was Co binder material having heavily deformed to fracture, separating the WC grains. Loss of strength in binder material at cutting temperatures

is also discussed. As would be expected, the general trend of how F increased as the number of pass (N_{pass}) increased agreed with the general trend of increasing flank wear (VB) as N_{pass} increased. However, the F-VB_{max} plot has shown a rather poor F-VB_{max} relationship. This was the result of the different modes of tool deterioration affecting VB_{max} differently, but VB_{max} did not represent fully the true cutting edge of the deteriorating tool insert. Chipping and breakage of the inserts confined in the cutting area, resulting in the significant blunting of the edge area, causing a high rate of F increase as VB_{max} increased and completely deteriorated 6 minutes within of milling time. Fracturing along the face of thin pieces effectively increased VB_{max} without increasing the cutting edge area and without further blunting the edge, thus no increase in F was required. The high rate, meaning high $\Delta F/\Delta VB_{max}$, results from the effect of the edge deterioration/blunting on the reducing the effective rake angle and thus increasing F is suggested and discussed. The use of coolant has not been found to affect tool deterioration/life and cutting force. Explanation for this will be given considering the deformation zone for which coolant does not have an effect. An increase in feed rate has reduced the tool life and the mode of deterioration has become more edge chipping/fracturing dominant, leading to a better F-VB_{max} relationship.

Finally, it has been observed that the rate of tool deterioration is not higher when the hardened workpiece material is used. The modes and progression of deterioration of tools using hardened workpiece were determined to be comparable to those when annealed workpiece was used. Furthermore, the trends of increase in cutting force as milling pass increases have been observed to be similar for both workpiece material conditions. Interrupt milling experiments followed by hardness mapping has indicted that the workpiece hardened state has not affected the deformation area significantly, although increase in hardness in a similar amount in the severe deformed region has been found for both cases. It is suggested that temperature increases in the narrow deformation zone to be similar for both workpiece conditions and at high temperatures hardening mechanisms do not operate, and thus cutting force values do not differ significantly. Furthermore, the modes and rate of tool deterioration on the hardened workpiece was comparable to the annealed workpiece.

ACKNOWLEDGEMENTS

I would like to acknowledge and extend my heartfelt gratitude to my primary supervisor, Prof Zhan Chen for the continuous support of my Ph.D study and related research, for his patience, motivation, and immense knowledge. His guidance helped me in all the time of research and writing of this thesis. I could not have imagined having a better advisor and mentor for my Ph.D study. I also would also like to thank my secondary supervisor, AP Timotius Pasang for his continuous support guiding me through the thesis writing process by giving me his best effort.

My sincere thanks also goes to Jim Crossen, Ross Jamieson, Mark Masterston, Tim Luton, Thomas Jones and Patrick Connor for their hard work, expertise and patience. Without their precious support, it would not be possible to conduct this research.

My appreciation also extends to Karl Davidson for stimulating discussion and for the sleepless nights we were working together before the deadline. I also would like to thank Doddy, Evtaleny, and Yuan and other research group members for all the fun we have had in the last three years. I also thank my dearest friends Hemyza Budin, Har Einur Azrin, Nurul Syuhada Mohamed, Ili Ayuni Johan and Ridhuan Abd. Rahim for providing support and friendship.

Most importantly, I would like to thank The Davidsons and Wendy Millen for their great support and unconditional love during difficult times. I would not have made it this far without them. Last but not least, I would like to thank my family especially my mother, Wan Rasnah Wan Idris, who have guided me throughout my life. She has always sacrificed her time and has continuously supported me in achieving my dreams and goals. I would like to thank her for all her love, support and encouragement for me. I specially dedicate this work to my beloved late father, Razak Latif and I wish he could smile for me.

LIST OF PUBLICATIONS

The following papers have been published over the course of this research.

Journal papers:

Razak, NH, Chen, ZW and Pasang, T, Modes of Tool Deterioration during Milling of 718Plus Superalloy Using Cemented Tungsten Carbide Tools, Wear 316 (2014): 92-100.

Razak, NH, Chen, ZW and Pasang, T, Progression of Tool Deterioration and Related Cutting Force during Milling of 718Plus Superalloy using Cemented Tungsten Carbide Tools, International Journal Advance Manufacturing Technology (2016) 86: 3203-3216.

Conference paper:

Razak, NH, Chen, ZW and Pasang, T, Relationship Between Tool Deterioration and Cutting force during Milling of a Nickel-Based Superalloy Using Cemented Carbide Tool, Proceeding of the ASME 2015 International Mechanical Engineering Congress and Exposition (IMECE2015), November 13-19, 2015, Houston, Texas.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

ω - Spindle Speed

$\tau_{Cutting}$ - Shear Stress

θ_e - Effective Rake Angle

a_e - Radial Depth of Cut

BUE – Build-Up Edge

BUL - Build-Up Layer

Co - Cobalt

CrN - Chromium Nitride

$d_{c\text{-}w}$ / h - Thickness of Cut

DoC - Depth of Cut

EDS - Energy Dispersive Spectrometry

f or FR - Feed Rate

F or $F_{Cutting}$ - Cutting Force

F_a - working plane

$F_{Cutting\text{-}R}$ - Cutting Edge Action Force

F_f - Friction Force

F_R - Resultant Force

F_x - Force in x-direction

F_y - Force in y-direction

F_z - Force in z-direction

$F_{x\text{-}m}$ - The maximum F_x started to decrease when the end of the pass was reached

$F_{y\text{-}m}$ - The maximum F_y started to decrease when the end of the pass was reached

$F_{z\text{-}m}$ - The maximum F_z started to decrease when the end of the pass was reached

F_m - The maximum F started to decrease when the end of the pass was reached

$F_{x\text{-}e\text{-}m}$ - The maximum F_x of 3 s period just before the insert reached the end of workpiece

$F_{y\text{-}e\text{-}m}$ - The maximum F_y of 3 s period just before the insert reached the end of workpiece

$F_{z\text{-}e\text{-}m}$ - The maximum F_z of 3 s period just before the insert reached the end of workpiece

$F_{e\text{-}m}$ – The maximum F of 3 s period just before the insert reached the end of workpiece

HRC - Hardness Rockwell C

HV - Hardness Vickers

ISO - International Organisation for Standardisation

MAZ - Milling Affected Zone

MQL - Minimum Quantity Lubrication

Ni - Nickel

N_{pass} - Number of Tool Passes

PCD - Polycrystalline Diamond

PVD - Physical Vapour Deposition

r_e - Cutting Edge Radius

$r_{e\text{-}eff}$ - Effective Radius of the Cutting Edge

SEM – Scanning Electron Microscope

t_0 - Original Cutting Edge Geometry

TC -Tool Condition

TDA - Tool Deterioration Area

t_i - Original Cutting Edge Geometry after the wearing process

TiAlN - Titanium Aluminium Nitride

TiC - Titanium Carbide

TiN - Titanium Nitride

v - Forward Speed

V - Tool Forward Speed

VB - Flank Wear

$VB1$ - Uniform Flank Wear

$VB2$ - Non-Uniform Wear

$VB3$ - Localised Flank Wear

VB_{max} - Maximum Flank Wear (localised)

V_c – Cutting Speed

VTW - Volume Tool Wear

V_{wear} - Volume of Wear

WC - Tungsten Carbide

WC-Co - Cemented Tungsten Carbide

ZPEO - Zero Pass Edge Outline

ATTESTATION OF AUTHORSHIP

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

Auckland Signature_____

References

[1] V. P. Astakhov, *Machinability of Advanced Materials*, First Edit. ISTE Ltd and John Wiley & Sons,INc, 2014.

[2] S. Pervaiz, A. Rashid, I. Deiab, and M. Nicolescu, "Influence of Tool Materials on Machinability of Titanium- and Nickel-Based Alloys: A Review," *Mater. Manuf. Process.*, vol. 29, no. 3, pp. 219–252, 2014.

[3] Y. S. Liao, H. M. Lin, and J. H. Wang, "Behaviors of end milling Inconel 718 superalloy by cemented carbide tools," *J. Mater. Process. Technol.*, vol. 201, no. 1–3, pp. 460–465, 2008.

[4] X. Q. Chen and H. Z. Li, "Development of a tool wear observer model for online tool condition monitoring and control in machining nickel-based alloys," *Int. J. Adv. Manuf. Technol.*, vol. 45, no. 7–8, pp. 786–800, 2009.

[5] K. Kadirgama, K. A. Abou-El-Hossein, M. M. Noor, K. V. Sharma, and B. Mohammad, "Tool life and wear mechanism when machining Hastelloy C-22HS," *Wear*, vol. 270, no. 3–4, pp. 258–268, 2011.

[6] A. Devillez, G. Le Coz, S. Dominiak, and D. Dudzinski, "Dry machining of Inconel 718, workpiece surface integrity," *J. Mater. Process. Technol.*, vol. 211, no. 10, pp. 1590–1598, 2011.

[7] S. Olovsjö and L. Nyborg, "Influence of microstructure on wear behaviour of uncoated WC tools in turning of Alloy 718 and Waspaloy," *Wear*, vol. 282–283, pp. 12–21, 2012.

[8] S. Zhang, J. F. Li, and Y. W. Wang, "Tool life and cutting forces in end milling Inconel 718 under dry and minimum quantity cooling lubrication cutting conditions," *J. Clean. Prod.*, vol. 32, pp. 81–87, 2012.

[9] irfan Ucun, K. Aslantas, and F. Bedir, "An experimental investigation of the effect of coating material on tool wear in micro milling of Inconel 718 super alloy," *Wear*, vol. 300, no. 1–2, pp. 8–19, 2013.

[10] M. Imran, P. T. Mativenga, A. Gholinia, and P. J. Withers, "Comparison of tool wear mechanisms and surface integrity for dry and wet micro-drilling of nickel-base superalloys," *Int. J. Mach. Tools Manuf.*, vol. 76, pp. 49–60, 2014.

[11] M. S. Kasim, C. H. Che Haron, J. A. Ghani, M. A. Sulaiman, and M. Z. A. Yazid,

"Wear mechanism and notch wear location prediction model in ball nose end milling of Inconel 718," *Wear*, vol. 302, no. 1–2, pp. 1171–1179, 2013.

[12] D. Zhu, X. Zhang, and H. Ding, "Tool wear characteristics in machining of nickel-based superalloys," *Int. J. Mach. Tools Manuf.*, vol. 64, pp. 60–77, 2013.

[13] S. Chinchanikar and S. K. Choudhury, "Machining of hardened steel - Experimental investigations, performance modeling and cooling techniques: A review," *Int. J. Mach. Tools Manuf.*, vol. 89, pp. 95–109, 2015.

[14] L. N. L. De Lacalle, A. Lamikiz, J. F. De Larrinoa, and I. Azkona, "Advanced Cutting Tools.", Machininhg of Hard Materials, Springer-Verlag, London, 2011, pp.33-86.

[15] ISO 8688-2, International Organisation for Standardization, Geneva, 1989.

[16] H. G. Prengel, W. R. Pfouts, and A. T. Santhanam, "State of the art in hard coatings for carbide cutting tools," *Surf. Coatings Technol.*, vol. 102, no. 3, pp. 183–190, 1998.

[17] A. Jawaid, S. Koksal, and S. Sharif, "Cutting performance and wear characteristics of PVD coated and uncoated carbide tools in face milling Inconel 718 aerospace alloy," *J. Mater. Process. Technol.*, vol. 116, no. 1, pp. 2–9, 2001.

[18] M. Kuttolamadom, "Prediction of the Wear & Evolution of Cutting Tools in a Carbide / Ti-6Al-4V Machining Tribosystem by Volumetric Tool Wear Characterization & Modeling," p. 258, 2012.

[19] M.-D. Jimenez, A.-E, Bermudez, "Friction and wear," in *Industrial Lubrication and Tribology*, vol. 36, no. 5, J. P. Davim, Ed. Woodhead Publishing Limited, 1984, pp. 168–169.

[20] M. C. Shaw, *Second Edition*, Second. Oxford series on Advanced manufacturing, , pp. 170, 2005.

[21] J. a. Charles, *Selection and Use of Engineering Materials*, Third. Butterworth Heinemann, 1997.

[22] H. Z. Li, H. Zeng, and X. Q. Chen, "An experimental study of tool wear and cutting force variation in the end milling of Inconel 718 with coated carbide inserts," *J. Mater. Process. Technol.*, vol. 180, no. 1–3, pp. 296–304, 2006.

[23] W. Akhtar, J. Sun, P. Sun, W. Chen, and Z. Saleem, "Tool wear mechanisms in

the machining of Nickel based super-alloys: A review," *Front. Mech. Eng.*, vol. 9, no. 2, pp. 106–119, 2014.

[24] E. O. Ezugwu, Z. M. Wang, and A. R. Machado, "The machinability of nickel-based alloys: a review," *J. Mater. Process. Technol.*, vol. 86, no. 1, pp. 1–16, 1999.

[25] E. O. Ezugwu, J. Bonney, and Y. Yamane, "An overview of the machinability of aeroengine alloys," *J. Mater. Process. Technol.*, vol. 134, no. 2, pp. 233–253, 2003.

[26] Y. Huang and S. Y. Liang, "Modeling of CBN Tool Flank Wear Progression in Finish Hard Turning," *J. Manuf. Sci. Eng.*, vol. 126, no. 1, p. 98, 2004.

[27] A. Shokrani, V. Dhokia, S. T. Newman, and R. Imani-Asrai, "An initial study of the effect of using liquid nitrogen coolant on the surface roughness of inconel 718 nickel-based alloy in CNC milling," *Procedia CIRP*, vol. 3, no. 1, pp. 121–125, 2012.

[28] D. Dudzinski, A. Devillez, A. Moufki, D. Larrouquère, V. Zerrouki, and J. Vigneau, "A review of developments towards dry and high speed machining of Inconel 718 alloy," *Int. J. Mach. Tools Manuf.*, vol. 44, no. 4, pp. 439–456, 2004.

[29] T. Obikawa, Y. Kamata, Y. Asano, K. Nakayama, and A. W. Otieno, "Micro-liter lubrication machining of Inconel 718," *Int. J. Mach. Tools Manuf.*, vol. 48, no. 15, pp. 1605–1612, 2008.

[30] Y. Kamata and T. Obikawa, "High speed MQL finish-turning of Inconel 718 with different coated tools," *J. Mater. Process. Technol.*, vol. 192–193, pp. 281–286, 2007.

[31] F. Pusavec, H. Hamdi, J. Kopac, and I. S. Jawahir, "Surface integrity in cryogenic machining of nickel based alloy—Inconel 718," *J. Mater. Process. Technol.*, vol. 211, no. 4, pp. 773–783, 2011.

[32] D. Fernández, V. García Navas, A. Sandá, and I. Bengoetxea, "Comparison of machining inconel 718 with conventional and sustainable coolant," *MM Sci. J.*, no. December 2014, pp. 506–510, 2014.

[33] A. Aramcharoen and S. K. Chuan, "An experimental investigation on cryogenic milling of inconel 718 and its sustainability assessment," *Procedia CIRP*, vol. 14, pp. 529–534, 2014.

[34] Y. Kaynak, H. E. Karaca, R. D. Noebe, and I. S. Jawahir, "Tool-wear analysis in

cryogenic machining of NiTi shape memory alloys: A comparison of tool-wear performance with dry and MQL machining," *Wear*, vol. 306, no. 1–2, pp. 51–63, 2013.

[35] J. A. Ghani, I. A. Choudhury, and H. H. Masjuki, "Wear mechanism of TiN coated carbide and uncoated cermets tools at high cutting speed applications," *J. Mater. Process. Technol.*, vol. 153–154, no. 1–3, pp. 1067–1073, 2004.

[36] A. Sharman, R. C. Dewes, and D. K. Aspinwall, "Tool life when high speed ball nose end milling Inconel 718™," *J. Mater. Process. Technol.*, vol. 118, no. 1–3, pp. 29–35, Dec. 2001.

[37] H. G. Prengel, P. C. Jindal, K. H. Wendt, A. T. Santhanam, P. L. Hegde, and R. M. Penich, "A new class of high performance PVD coatings for carbide cutting tools," *Surf. Coatings Technol.*, vol. 139, no. 1, pp. 25–34, 2001.

[38] L. Li, N. He, M. Wang, and Z. G. Wang, "High speed cutting of Inconel 718 with coated carbide and ceramic inserts," *J. Mater. Process. Technol.*, vol. 129, no. 1–3, pp. 127–130, 2002.

[39] C. Ducros, V. Benevent, and F. Sanchette, "Deposition, characterization and machining performance of multilayer PVD coatings on cemented carbide cutting tools," *Surf. Coatings Technol.*, vol. 163–164, pp. 681–688, 2003.

[40] M. Sortino, S. Belfio, G. Totis, E. Kuljanic, and G. Fadelli, "Innovative tool coatings for increasing tool life in milling Nickel-coated Nickel-Silver alloy," *Energy Procedia*, vol. 100, no. C, pp. 946–952, 2015.

[41] X. Kong, L. Yang, H. Zhang, K. Zhou, and Y. Wang, "Cutting performance and coated tool wear mechanisms in laser-assisted milling K24 nickel-based superalloy," *Int. J. Adv. Manuf. Technol.*, vol. 77, no. 9–12, pp. 2151–2163, 2015.

[42] B. Kaya, C. Oysu, and H. M. Ertunc, "Force-torque based on-line tool wear estimation system for CNC milling of Inconel 718 using neural networks," *Adv. Eng. Softw.*, vol. 42, no. 3, pp. 76–84, 2011.

[43] M. Nouri, B. K. Fussell, B. L. Ziniti, and E. Linder, "Real-time tool wear monitoring in milling using a cutting condition independent method," *Int. J. Mach. Tools Manuf.*, vol. 89, pp. 1–13, 2015.

[44] S. Chinchanikar and S. K. Choudhury, "Cutting force modeling considering tool wear effect during turning of hardened AISI 4340 alloy steel using multi-layer

TiCN/Al2O3/TiN-coated carbide tools," *Int. J. Adv. Manuf. Technol.*, vol. 83, no. 9–12, pp. 1749–1762, 2016.

[45] C. H. Lauro, L. C. Brandão, D. Baldo, R. A. Reis, and J. P. Davim, "Monitoring and processing signal applied in machining processes - A review," *Meas. J. Int. Meas. Confed.*, vol. 58, pp. 73–86, 2014.

[46] L. Whitmore *et al.*, "The microstructure of heat-treated nickel-based superalloy 718Plus," *Mater. Sci. Eng. A*, vol. 610, pp. 39–45, 2014.

[47] T. D. Sheet, "ATI 718Plus ® Alloy 1," vol. 1, pp. 1–5, Allegheny Technologies Incorporated, 2013.

[48] V. P. Astakhov, "The assessment of cutting tool wear," *Int. J. Mach. Tools Manuf.*, vol. 44, no. 6, pp. 637–647, 2004.

[49] M. Kuttolamadom, P. Mehta, L. Mears, and T. Kurfess, "Correlation of the Volumetric Tool Wear Rate of Carbide Milling Inserts With the Material Removal Rate of Ti–6Al–4V," *J. Manuf. Sci. Eng.*, vol. 137, no. 2, p. 21021, 2015.

[50] M. A. Kuttolamadom and M. L. Mears, "Msec2011-50278 on the Volumetric Assessment of Tool Wear in Machining," pp. 1–10, 2011.

[51] Chetan, B. C. Behera, S. Ghosh, and P. V. Rao, "Wear behavior of PVD TiN coated carbide inserts during machining of Nimonic 90 and Ti6Al4V superalloys under dry and MQL conditions," *Ceram. Int.*, vol. 42, no. 13, pp. 14873–14885, 2016.

[52] N. H. Razak, Z. W. Chen, and T. Pasang, "Modes of tool deterioration during milling of 718Plus superalloy using cemented tungsten carbide tools," *Wear*, vol. 316, pp. 92–100, 2014.

[53] A. Introduction, M. F. Ashby, and D. R. H. Jones, *Engineering Materials 2*. 1986.

[54] T. Kitagawa, A. Kubo, and K. Maekawa, "Temperature and wear of cutting tools in high-speed machining of Inconel 718 and Ti□6Al□6V□2Sn," *Wear*, vol. 202, no. 2, pp. 142–148, 1997.

[55] L. Zhang, X. Qu, X. He, D. Rafi-Ud, M. Qin, and H. Zhu, "Hot deformation behavior of Co-base ODS alloys," *J. Alloys Compd.*, vol. 512, no. 1, pp. 39–46, 2012.

[56] R &D ISCAR Ltd., "of ISCAR Grades Substrate - IC 28 Grade - IC 928 Typical Layers," *Gen. Inf. ISCAR Grades*, p. 9970165, 2013.

[57] X. Ren and Z. Liu, "Influence of cutting parameters on work hardening behavior of surface layer during turning superalloy Inconel 718," *Int. J. Adv. Manuf. Technol.*, pp. 2319–2327, 2016.